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MACHINE CASTING OF FERROUS ALLOYS

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This final report of a three-year program contains some highlights of the earlier reports and much detail about Rheocasting and the casting of aluminum containing superalloys by Hitchiner's patented CLA process. Aluminum castings were made using metal up to about 25% solid and steel castings using 10% solid metal were also made. No improvement in casting quality was noted in either case. GMR 235 and Inco-713LC alloys cast

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by CLA showed excellent properties. Some of these turbine wheels submitted to a major turbocharger manufacturer passed the qualification test. Low pressure reusable mold processes for casting ferrous alloys were not economical because of inadequate die life and hot tearing of the castings.

FOREWORD

This report covers work done in the period 1 February 1973 - 27 February 1976, under the general title "Machine Casting of Ferrous Alloys". The work is sponsored by the Defense Advanced Research Projects Agency under ARPA Order No. 2267, Program Code No. 4D10. The work was carried out at the Hitchiner Manufacturing Company, Inc., Elm Street, Milford, N.H. 03055, by the principal investigators, G. D. Chandley and Gary Scholl, (Tel: (603)673-1100). The work was accomplished under Contract No. DAAG46-73-C-0112 with Dr. E. Wright/Mr. Frank Quigley at Army Materials and Mechanics Research Center as the program technical monitor.

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INTRODUCTION

Hitchiner's role in the machine casting of ferrous alloys program was to develop a process satisfactory for ferrous castings weighing up to about one pound. A review of the references at the end of this report indicated that an economic process for such parts would require very innovative approaches. Attempts to make such castings using high injection pressures were unsuccessful due to short mold life. It was felt that low pressure mold filling would be better. Two approaches to low pressure mold filling were to charge the metal between the mold halves of an open mold and secondly, to vacuum metal into a closed mold. Much work was done in these techniques and this was reported in AMMRC reports 74-16, 74-52, 75-9, and 75-18, Contract No. DAAG46-73-C-0112. From the standpoint of mold filling, the Hipocast procedure was satisfactory. However, it was uneconomical due to hot tearing of the castings and inadequate mold life.

In parallel to work at Hitchiner, M.I.T. was casting with Thixotropic metal. Hopefully, use of this type of metal would reduce the hot tear mold life problems. While M.I.T. pursued that approach, the Advisory Board decided Hitchiner should make Rheocastings with disposable molds and also to investigate the casting of nickel-base super alloys in Hitchiner's patented machine casting process (U.S. Pat. No. 3,863,706).

WORK ACCOMPLISHED

DEVELOP NEW APPROACHES TO MACHINE CASTING

The broad objectives of this research were 1) to seek out new and creative methods for machine casting small size (up to one pound) ferrous parts, 2) to develop and refine the best of these methods into a viable and more economic production process; and 3), to establish a profitable ferrous die casting fa. .ity. Several feasible systems for machine casting ferrou: loys were conceived and evaluated. Most of these systems were implemented in varying degrees to examine the critical parameters inherent in each design. Frequently liquid wax analogs were used during this early evaluation period. The use of wax simplified control of time-temperature events, eliminated material selection problems and permitt simplistic approaches to evaluating casting soundness. Later, prototypes were tested using aluminum and copper-base alloys.

The primary motivation for each of the designed systems was to obtain a cost effective process that could be easily controlled in a production environment. To accomplish this objective, each segment of the traditional machine casting cycle was examined. These segments are:

1) melting and holding specified alloy,
2) applying ablative coatings to die surfaces,
3) transporting charge from melter and loading injection reservoir,
4) injecting liquid metal into the die cavity,
5) solidifying the liquid metal,
6) extracting the solidified casting.

An important design concept evolved from this examination; through creative design, the melting facility could function as the injection reservoir, thereby eliminating an entire step in the casting cycle. A second design concept evolved with the realization that the complications inherent in all solid ram-injection systems, such as abrasion, differential thermal expansion and the ever present material requirements accompanying high temperature service, could be eliminated by several means.

Hipocast Process

The Hipocast process involves the insertion of open, permanent dies into the holding furnace; then, closing the dies while immersed in the liquid metal. (See Figure 1). This process has several advantages over conventional die casting methods. Among these are:

a) the elimination of a liquid metal transfer system and accompanying separate injection reservoir,
b) the elimination of turbulence porosity caused by the nozzle effect of injecting liquid metal into a gas filled cavity through constricted gates, and
c) ease of controlling operating parameters.

This method yielded good casting soundness which could be perfected through proper risering and achieved encouraging results when evaluated by casting several complex geometries. See Figure 2.

A semi-automated prototype machine was designed and fabricated (see Figure 3) to examine the production aspects of the Hipocast process. During the refinement phase of this research, the major problem areas were studied concurrently with the primary objective of continuous system operation.

One of the first problems to be dealt with was metal pickup on the external surfaces of the dies. This metal formed a shell which encompassed and contained the two die halves impeding timely extraction of the solidified casting. The machine design did not provide sufficient force to separate the dies when this shell was more than 1/32 inch thick. Numerous coating agents were tested to prevent wetting of the dies external surfaces by the molten metal. The ultimate solution to this problem was to apply by venturi spray, ablative laminations of calcined china clay followed by Colloidal graphite.

Initially it was expected that casting extraction would present a major problem in that capillary action of the molten metal would soon erode and then abrade the sliding surfaces of extraction pins. It was found that with proper die design and a light ablative coating of acetylene soot, the casting can be easily extracted from the containing die section. The major process related problem area arises from the thermal contraction occurring during cooling and solidification which results in hot tears for most complex shapes. The hot tear problem is further complicated by the thin flash created in the Hipocast process.

The second process design concept that was investigated has the same advantages realized by the Hipocast process (incorporates injection reservoir with melting unit and does not require a ram-injecting system) and eliminates the major disadvantages of the Hipocast process (exterior surfaces of the die do not come in contact with molten metal, and parting line flash is all but eliminated). This concept uses differential gas pressures to fill a closed mold through an opening which is introduced into the melting and holding reservoir.

Thermedix Process

The Thermedix Process, see Figures 4 and 5, pressurizes the reservoir to force molten metal into the die cavity. This process was implemented for ferrous casting but major difficulties arose in the area of seal design at the mold/melter interface. Because some metal always solidifies at this mating line, the use of permanent seals caused major extraction difficulties and expendable seals, which met dimensional requirements, could not be economically justified.

The Vacuum Injection System

The vacuum injection system or CLD process (see Figure 6) has the same advantages of the Thermedix process and eliminates the requirement for a seal at the die - reservoir interface. The control of rate of change of pressure is essential in this process to eliminate overshoot of the metal into the vacuum exhaust lines and it was difficult to eliminate air entrapment in solid dies of complex geometry. Success has been achieved with this process design concept using porous investment shell molds in the Hitchiner patented CLA Process, and therefore some time was spent in search of a porous die material.

Control of Melt Temperature

The melt temperature must be accurately maintained for extended periods of time in an integrated machine casting process. It was reasoned that temperature should be automatically controlled and not subject to periodic operator measurement. To accomplish this, a thermocouple was placed in a protective sheath (Cermotherm) a calculated distance below the surface of the ram lining, near the bottom of the melter. The thermocouple output was processed by a current adjusting type controller (L&N Electro-max III) which operated the power control (Inductotherm VIP 250) to the melting coil. The distance below the surface was calculated on the basis of the melting unit's response to full power input, and the thermal properties of the MgO furnace lining. Naturally the sheath was better protected but less responsive as depth from the surface increased. This system was found to perform satisfactorily in applications of extended holding times but was not suitable for situations demanding rapid changes in temperature.

DEVELOPMENT OF MOLD SYSTEMS

Thus, while part of the program was directed toward development of a casting process which would make good quality castings at low metal pressures to reduce die fatigue, a second part of the program was to see if known or new mold types would be suitable using these gentle casting methods. Economic evaluations based on the investment casting process will be reported in detail by M.I.T.

The following criteria was established for an adequate mold system:

1) The ability to withstand $3000^{\circ}F$.
2) The ability to react to dimensional changes of the casting.
3) Freedom from chemical reactions which may cause surface and gas defects.
4) The ability to maintain surface and dimensional integrity.
5) The contribution of the mold system cost to each casting should not exceed 25 cents for an 8 oz. part.

Permanent Metal Molds

Numerous die materials were evaluated by gravity pouring into permanent molds. It was confirmed that performance was significantly related to the dies ability to transfer thermal energy from the casting to the bulk mass of the die. Good results were achieved with chrome-copper dies but, high temperature strength and oxidation problems existed with these copper alloys. Tool steels and super-alloys, on the other hand, transferred heat more slowly, resulting in higher die surface temperatures, which caused welding after several cycles, or if run on longer cycles, dies would thermally crack in a few hundred cycles. Refractory and heavy metal die materials were longer lasting but were found to be extraordinarily brittle and, as such, were prone to catastrophic failure at any time. The overall cost effective selection for die materials appeared to be H-13 tool steel, cast to shape and finish machined.

Composite Dies

A composite die consisting of a thin, high temperature alloy shell, backed by a high diffusivity bulk material, was considered as a possibility to fulfill the requirements for a low cost die. Further, if the back up material were in liquid phase, a near perfect thermal interface would result between the two materials.

Finally, by selecting a back-up material with a melting range within the desired die temperature operating range, thermal cycling of the composite die would be significantly stabilized by the absorbtion and rejection of latent heat of fusion in the back-up material, see Figure 7.

Although the extremely low diffusivity of superalloys still rendered them ineffective for the thin shell, H-13 tool steels in thicknesses of .040"-.080" yielded significant results when backed with liquid 6061 aluminum. These results were encouraging but were not consistent. Frequently, welding occurred at the bottom of the gravity poured cavity. Upon dismantling the fixture, it was found that a void had developed beneath the weld spot. It was not then evident whether this pocket represented the cause or effect of welding. If the void was present prior to metal entering the mold, poor heat transfer would result across the void, and the shell temperature would rise at that point causing welding. Such voids could also result from solidification shrinkage at a "hot spot" caused by welding.

The concept of utilizing an aluminum back-up material was pursued by designing and manufacturing a set of dies to be tested in the Hipocast machine. The posture of the Hipocast dies assures pressurized intimate contact between the die material (H-13) and the liquid aluminum back-up material without three dimensional containment. Further, because the interface is vertical instead of horizontal, the entrapment of gas bubbles at the interface is virtually impossible. The results of this test were discouraging in that failure was caused by the formation of a shrink void in the back-up material; the thermal shock to the shell in the next cast was thus very severe, causing progressive local failure. The die was bisected (see Figure 8) which revealed that at some point in time the crack opened while immersed in the molten steel, allowing the steel to flow into the back-up region and displace aluminum. There the steel solidified leaving the shrink pockets which are exposed.

Follow up tests were conducted using tin as the back up material to eliminate the possibility of phase changes occurring. The low number of cycles to failure here were attributed to the low conductivity of tin in the liquid phase. It became clear that mold amortization costs for parts of any complexity in a machine casting process for ferrous alloys precluded the use of conventional metallic dies, and alternative mold systems were sought.

Aspi-cast System

An aspirating die system was conceived and implemented in several stages for investigation. Porous metal molds were fabricated by a powdered metals process. These inserts (containing the casting cavity) were placed in specially designed fixtures which created a vacuum behind the porous mold. The pressure differential across the mold to atmosphere was then used to maintain a thin coating of dry refractory particles at the exposed surface of the porous insert. The system relied on the refractory particles to protect the die materials from intimate exposure to the casting environment and allows for easy expulsion of the coating and casting by pressurizing the mold.

Techniques were developed to coat the dies and gravity pouring tests were accomplished. This system had several drawbacks primarily related to the fabrication process. High conductivity copper base material experienced melting of some phase constituents and ferrous materials were prone to oxidation. After a few casts the pores became plugged and the surfaces were not coated properly. Lack of pore uniformity was encountered in the production of dies with other than simple geometries.

Hipo-V Process

An investigation was also initiated to evaluate the possible advantages of a mold system which totally creates the cavity in unbonded sand using a light vacuum and a low permeability membrane. The sequence of events can best be described by the schematic illustrations in

Figure 9. Essentially, the process begins by vacuum forming a thin membrane to a porous pattern board. This board and membrane is then placed against a hollow die, which is subsequently backfilled with sand. Finally the die is evacuated of remaining air and atmospheric pressure is returned to the pattern board. This effectively transfers the membrane, still retaining the pattern surface geometry, to the die.

Preliminary tests were accomplished using a polyethylene film stretched and vacuum formed over a pattern which was mounted to porous metal plate. The first castings to be made using this mold system and the Hipocast machine appear in Figure 10. The surface texture which appears here was improved upon slightly by selecting finer sands for the mold and by decreasing the vacuum pressure in the mold to reduce penetration. It was apparent however, that to achieve the desired surface roughness (100-250 micro-inch) the mold had to be altered to cause pressure molding of fine sand grains at the membrane surface.

Augmented Hipo-V Process

An improved system was later pursued which incorporated a porous ceramic coating between the membrane and the sand mold. The ceramic was deposited in an ethyl silicate and flour slurry and then rapidly gelled chemically. The advantages of such a mold system are numerous and excellent surface and geometric integrity can be achieved. Although several steps are required to complete the casting cycle, the system appeared to lend itself to full automation and the short casting cycle times associated with machine casting. The ceramic coating, although permeable, supported the mold face without the cavity forming membrane. Further, with the membrane removed, the permeable mold was suitable for vacuum casting of high temperature liquid or semi-liquid metals. The sequence of events for the casting cycle are illustrated in Figure 11.

A suspension bomb lug (appearing in Figure 12) was selected for process evaluation because existing casting processes could not compete with production costs for this part as a machined forging.

The material selection for the low permeability membrane was an important aspect in the development of this process. Early tests were conducted using readily available polyethylene films marketed as food packaging wraps. These materials had an added advantage in that once transferred to the mold, they could be easily ignited and burned off while curing the ceramic coating.

Although the overall elongation of the parting membrane for the bomb lug part was around 200%, the complex geometry of several selected areas requires elongation which may exceed 800%. This led to an investigation of elastomers. An important criteria for elastomers, in light of their high costs, was reusability. This evolved to mean

1) Alkali and Acid resistance

2) General resistance to chemical attack

3) Low porosity

4) Availability in thin sheet form

5) Heat resistance

6) High elasticity

Several natural and synthetic rubbers were tested, and reasonable performance was achieved using a teflon mold release to protect the natural rubbers.

The ceramic coating was applied by spraying alternating layers of ceramic slurry, gelling agent and stucco sand onto the formed release membrane. The slurry consists of zircon flours suspended in a partially hydrolyzed ethylsilicate binder. These materials were readily available and in use daily at Hitchiner's shell building facilities for the production of investment casting shell molds. Several minor alterations of the slurries were necessary, however, to adjust the gelation time and the viscosity for compatibility with the process requirements and spray apparatus.

Prior to casting, the alcohol solvent in the ceramic coating was ignited by a low temperature flame. This insured completion of the gelling reaction and drove off any remaining moisture. The resulting coating contains numerous microscopic cracks but these are not readily visible to the unaided eye nor are they visible on the casting.

Castings made with the Augmented Hipo-V Process were prone to gross gas inclusions, resulting from the completion of mold reactions, in areas with thin cross sections. The most discouraging observation, however, was the continuation of the Hipocast hot tear problem. Several tests were conducted to try vacuuming the metal into the mold with some success but the requirement for an economic mold face remained unresolved.

EVALUATION OF RHEOCASTING WITH THE CLA PROCESS (U.S. Pat. 3,863,706)

Introduction to Rheocasting

Research at the Massachusetts Institute of Technology in the rheology and possible applications of partially solid metals has progressed from the investigation of low melting point alloys to ferrous metals. These partially solid slurries are produced by the controlled cooling of liquid metals which are simultaneously experiencing high shear velocities induced by stirring or similar means. The objective of that program, pertinent here, is the application of semi-solid ferrous alloys to a machine casting process. The rational being that this metal causes less thermal impact on mold materials than super heated liquid metals because it is already partially solidified.

There are two distinct approaches to the casting of semi-solid metals. The first, pursued exclusively at M.I.T., utilizes the highly thixotropic nature of this liquid solid mixture. These materials have the property to behave as a solid under the application of low shear forces but flow readily when increased shear forces are applied. In concept the thixocasting process is accomplished by loading a partially solid slug (which can be handled much like a section of solid bar stock) into the injection chamber of a device similar to a high pressure die casting and then causing the metal to flow into the mold cavity under the high shear forces generated by the injecting ram. This process permits the separate production of semi-solid charge stock which can be completely solidified and then reheated just prior to thixocasting.

The rheocasting process, evaluated at Hitchiner, involves the casting of batch produced partially solid metals. In this process the partially solid metal is cast directly into the mold cavity where solidification is completed. It was desired to determine the economic advantages of casting semi-solid metals by the CLA process.

Rheocasting Aluminum

A device used earlier by the M.I.T. group for the batch production of partially-solid aluminum alloys was moved to the Hitchiner Technical Center at Milford, N.H. for the purpose of gaining experience with the properties and handling characteristics of rheocast metals. After accomplishing minor alterations to the rheocast machine, sample castings were made with surprising ease using the CLA casting process. Figure 13 shows the casting apparatus used in this phase of testing and Figure 14 illustrates some of the geometries produced by casting semi-solid aluminum (up to 15%) into shell molds. Some were cast at 25% solid.

An investigation of mechanical properties conducted for 355 Al with rheocast structures of up to 30% solid revealed a relatively constant value around 30 ksi. Figure 15 shows the suspected percent solid vs. temperature for this alloy developed from experimental data. Test bars and castings made by this technique were found to be porous, drossy and generally of poor metallurgical quality. This is attributed to the techniques required to maintain the fluidity of the partially solid metal. Here two syncronized overlapping stirring paddles rotated continuously to keep the metal in shear. The negative effect of this action was to mix in the oxidized surface metal and further to entrap air in the melt. Although difficulty was encountered in filling out several of the sample geometries when solid concentrations exceeded 10-20%, it is believed that this problem could be corrected by preheating molds and/or increasing filling rates.

The excellent fillout that did occur for metal temperatures near the liquidus gave rise to speculation on the possibility of CLA pouring aluminum compressor wheels. These castings are presently being produced in open investment shell molds and cast under pressure directly against a chill surface. It was hoped that by using the CLA process, the metal could be poured at lower temperatures into colder molds to achieve superior mechanical properties. A single wheel was mounted on a CLA sprue in such a manner that during casting the base of the impeller wheel would be facing upward. After shell building the base section was removed from the mold and replaced with an aluminum chill block. Although the casting quality was not satisfactory, the mechanical properties were found to be clearly acceptable. This test was significant for other reasons. The CLA process had been devised to cast a large number (100-300) of small (1-2 oz.) castings on a single sprue. Although larger castings had been made in the past, this represented a dimension to the process not previously pursued. The possibility of economically producing larger castings (up to several pounds) with small (1/8-3/16 inch) equiaxed grain structures could have far reaching effects on the metals casting industry.

CLA Pouring High Strength Steel

A pilot investigation of strength properties developed by low temperature pouring high strength steels was initiated. Low alloy 4330 steel was poured at various temperatures from -30 to +70 degrees F above the liquidus. The mechanical properties appeared to be reasonable in the heat treated condition for castings poured more than 30°F above the liquidus and the quality was satisfactory when evaluated by non-destructive testing. Castings poured below the liquidus contained extensive internal voids.

DEVELOPMENTS IN AIR CASTING HIGH TEMPERATURE SUPER ALLOYS

For the best use of the program money, the ARPA Advisory Board recommended that Hitchiner use its remaining time in the program toward the casting of nickel-base super alloys using the CLA Process. Nearly all melting and casting of nickel base super alloys is now being accomplished by vacuum induction melting to preclude contamination by gases (specifically oxygen, hydrogen and nitrogen) and to control the composition of highly reactive elements. It was hoped that the key to success here would be the unique ability of the CLA Process to fill a mold with liquid metal taken from below the surface of the melt where it is somewhat protected and free of floating slag.

Turbine Wheel Background

The turbine wheel was selected because of its geometry (see Figures 16 and 17) weight (12-16 oz.) and the expanding market for defense and commercial applications. A turbocharger utilizes the expansion of exhaust gases from an internal combustion engine to drive a turbine wheel which, by direct mechanical linkage, turns a compressor wheel to feed combustion gases into the engine. It is characteristic of exhaust gases that this normally unused energy is greatly increased in times of demand performance. Therefore, an engine equipped with a turbocharger can perform in demand situations to provide increased power with significant material and energy savings. The mechanical-thermal properties of the turbine wheel are quite stringent because in addition to the high stress requirements at elevated temperatures the fatigue strength must be sufficiently high. All stress levels were further increased as the use of turbochargers was extended from aircraft applications to service in land vehicles which, due to requirements for wide range responsiveness, called for drastic reductions in materials at the outer perimeter.

The materials initially selected for use in turbochargers were cobalt alloys long recognized for their high temperature strength. With advancements in Jet Engine design and an accompanying demand for properties and geometries no longer producible as forgings, came the development of castable Ni-base super alloys for use as blades and vanes. Following further increases in metallurgical requirements, vacuum induction melting has become the only consistent means of meeting the specified properties in a production environment. As vacuum melting came into increased utilization and specifications for turbine wheels become more demanding, the alloy changes were made to Ni-base alloys and the vacuum requirements were retained. It is hoped that the air melting and casting technique proposed here would realize significant cost savings in the production of turbine wheels.

Introductory Testing

The first wheel to be tried weighed 4 pounds in Co-21 alloy and had a major diameter of 5-1/2 inches. (See Figure 16). The process limitations were quickly identified when it was realized that the time for a sprue with one part to complete solidification was in excess of 3 minutes. The lower chamber of the existing CLA apparatus was not designed to operate in the vicinity of molten metal for periods in excess of sixty seconds and the production rate was too slow to realize economic advantages. Several rapid calculations revealed that unlike the standard investment casting process, the shell mold would have to contain all the heat extracted from the molten metal. Tests which used various methods of side mounting gates were further plagued by frequent mold fractures caused by the weight and the large moment arm. On the positive side, sectioning revealed fine equiaxed grains throughout and only scattered minor inclusions upon microscopic evaluation. It was believed that non-fill which occurred on some fin tip areas could be eliminated by slight alteration of the shell building techniques and minor changes in the pouring parameters.

A smaller turbine wheel (3 inch major dia., 12 oz.) was selected to be cast in Inco Alloy 713LC (See Figure 17). One of the first tasks was to evaluate possible differences between wheels poured in vacuum and those cast in air by the CLA process. The stress rupture and tensile properties for cast to size and heat treated test bars were found to be satisfactory for both processes. (Chemical analysis and mechanical properties appear in Tables I and II). The initial differences were seen in the selection of pouring parameters. Vacuum pouring required an additional 100°F superheat in the metal and an additional 250°F superheat of the mold to achieve comparable fill out of the fin tips. A more startling difference was observed in the metallurgically prepared cross sections. The variation in grain structures for parts poured with the two processes is illustrated in Figure 18. Here can be seen the real advantage which results from the low thermal parameters made possible with the CLA process. The cross sections displayed frequent oxide inclusions which were often accompanied by micro porosity and the zyglo indications were extensive.

Quality Improvement

The bulk of the analytical work in nickel base super alloys was accomplished with GMR 235 (originally an air melt alloy). Early comparisons of castings poured by the CLA and vacuum melting processes were similar to those achieved with the Inco alloy. (Chemical analysis and mechanical properties appear in Tables I and II. The obvious problem with oxide inclusions had to be dealt with and a series of tests was devised to identify the nature of these inclusions and to examine the feasibility of excluding them from the casting.

Initially a shielding technique which utilized inert argon gas to displace air in the mold was tried. Schematically this apparatus is illustrated in Figure 19. The procedure used is as follows: 1) Open valve A and exhaust mold chamber, 2) Open valve B and delay closing valve A to draw argon through mold and fill entire system, 3) Open valve C, delay close valve B and remove temporary chamber. The mold was then continuously flushed with argon until the snout dipped below the surface of the molten metal. Control valve A was then opened and valve C closed to fill the mold. The opening and closing of valves was ultimately controlled by relay logic and timer signals.

It was reasoned that with the mold relatively free of oxygen the only oxides to reach the castings would be those floating on the surface of the metal and trapped by the descending snorkel. A floating device for the melter containing an argon gas diffuser was tried, and a floating inverted cup was placed in the mold to capture the separated disc of slag. Another technique was to provide an over flow area to capture the first metal flowing up the sprue. The best solution included closing off the existing mold opening allowing side entry of the metal into the filling snout.

Careful examination of the castings cross sections revealed that the remaining oxide inclusions were concentrated in several fins. It was determined that this was due to the bouyancy of the oxides and that by changing the orientation of the casting from horizontal to vertical, nearly all remaining oxides could be floated out of the casting and into the gating system. Several later changes in the gate design were found to further improve quality by streamlining the metal flow into the cavity. A photo of the sprue design appears as Figure 20.

Two areas remain to be investigated at the close of this project. The first is the elimination of small (.5mm dia.) gas inclusions which frequently appear in castings and are suspected to be caused by the gating system. The second relates to the evaluation of a ceramic fiber material to be used in the mold as an oxide filter. These fabricated filters were ordered but have not been received as of this writing.

Some turbocharger wheels which met specification were made and sent out for qualification testing. These did pass testing and further work in this area will be sponsored by private industry.

CONCLUSIONS

Except in special cases, ferrous die casting will not approach economic viability by the mere substitution of the available high temperature materials into machines now used for die casting zinc and aluminum alloys unless thixocast charges greatly increase die life and reduce hot tears.

Die material evaluations, which included heavy metal refractory materials, hard metals, nickel-base super alloys, copper base alloys and tool steels, indicated that the most economic selection of a die material would probably be H-13 tool steel.

Several approaches to process design have been investigated but economic viability of any is dubious. It was found that cost considerations continue to point toward single use, recycleable, porous molds composed essentially of granular refractory ceramics. The benefits of using these mold materials extends beyond the cost aspects into process advantages to reduce hot tear potential, enhance fillout, and reduce porosity.

The Hipocast concept, although possessing numerous process advantages, must be considered inapplicable for small ferrous castings because of the hot tear problem, as well as the lack of a suitable mold material.

Conceptually, the filling of the expendable mold by the application of a light vacuum is the best method for machine casting ferrous alloys. This offers the advantages of good fillout, closed mold, and the elimination of costly injection systems. The method was found to be effective in filling the mold cavity with fluid metal comprised of up to thirty percent solids.

The problem of dross inclusions inherent in batch preparation of semi-solid metals for the rheocast process remains unresolved.

The casting of nickel base super alloys by the patented CLA process was demonstrated to be economically viable; it also provides certain operational and material property advantages.

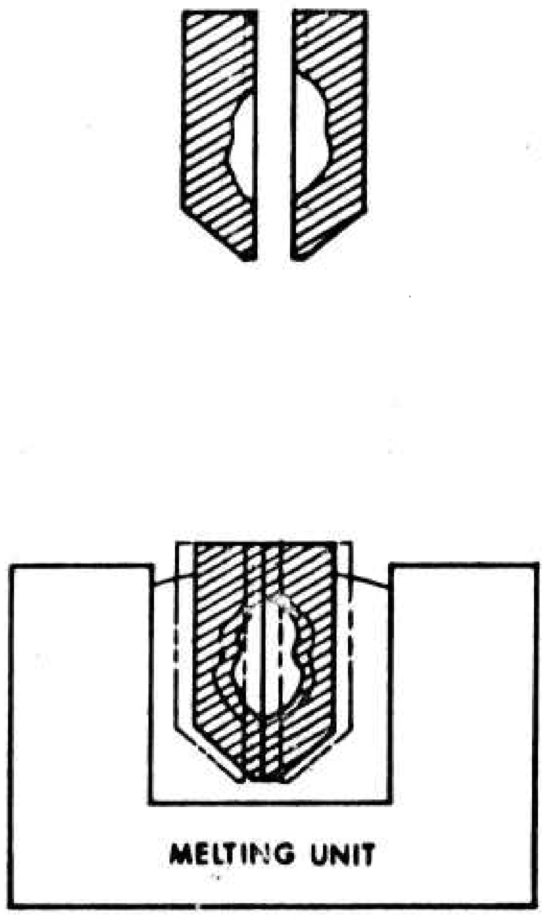


Figure 1. Schematic of Hipocast Process

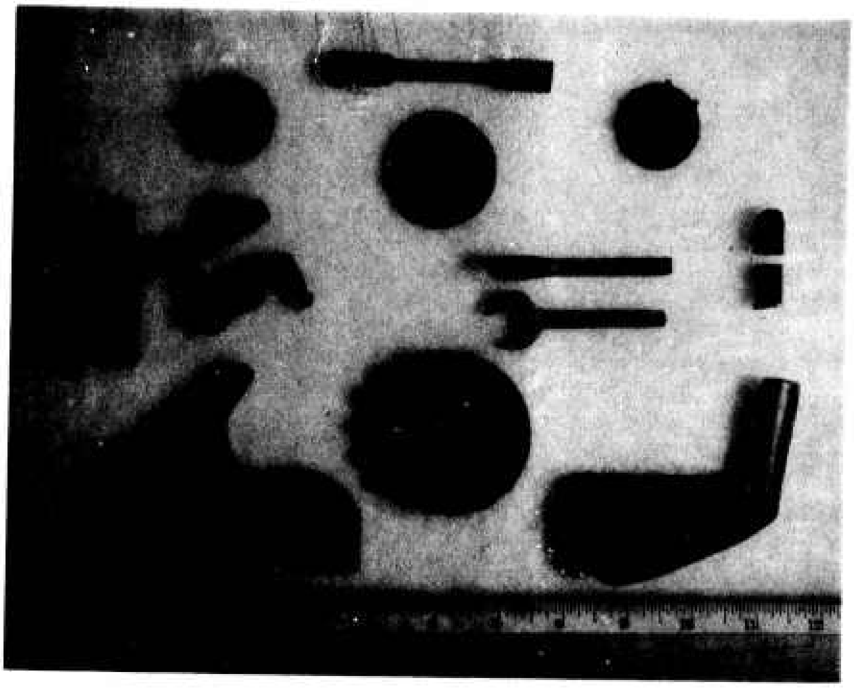


Figure 2 - All of the parts cast on the prototype Hipocast machine. Parts shown are:

Top Row - tensile test bar, 2 oz.

Second Row - star sprockets (2 oz.) and test medallion (2 oz.)

Third Row - striker plate (0.6 oz.), M-16 Rifle Hammer (0.8 oz.), Wrench (1 oz.), Clamp Jaw (0.3 oz.)

Bottom - Combination square frame (7 oz.), Gear Blank (13 oz.) and golf club head (9 oz.)

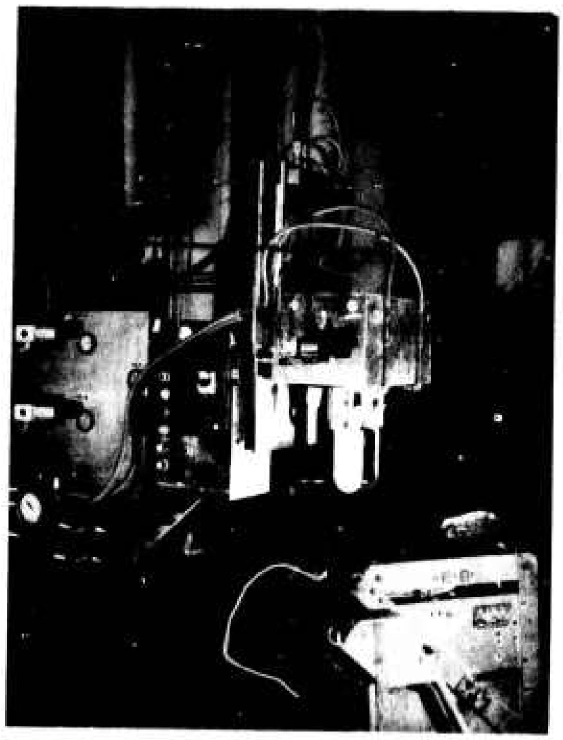


Figure 3. Prototype Hipocast Machine

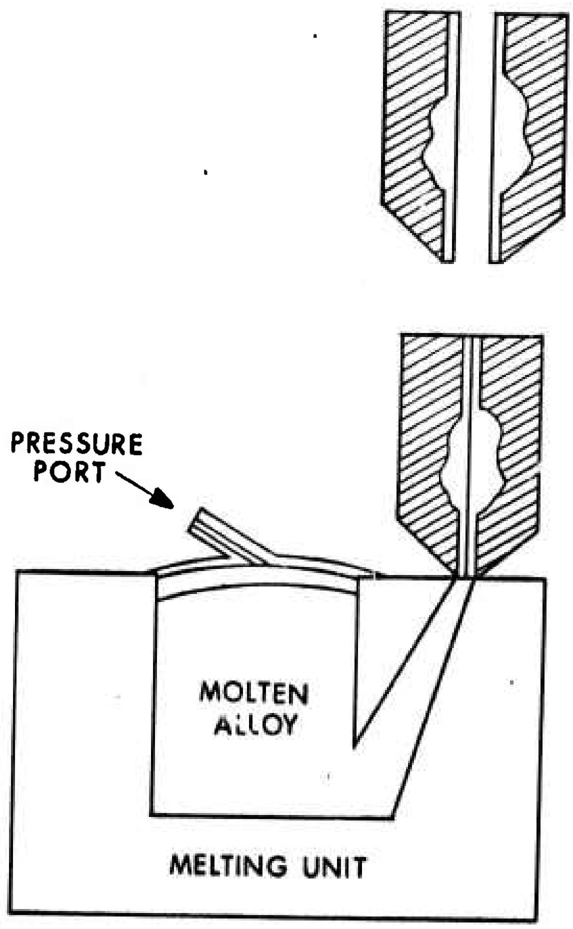


Figure 4. Schematic of Thermedix Process

Figure 5. Apparatus for Thermedix Process.

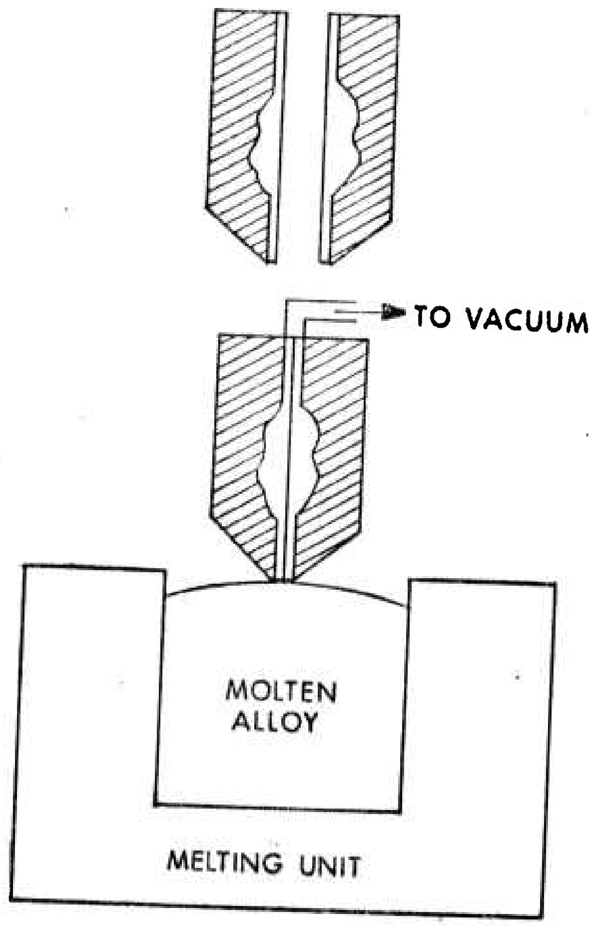


Figure 6. Schematic of CLD Process

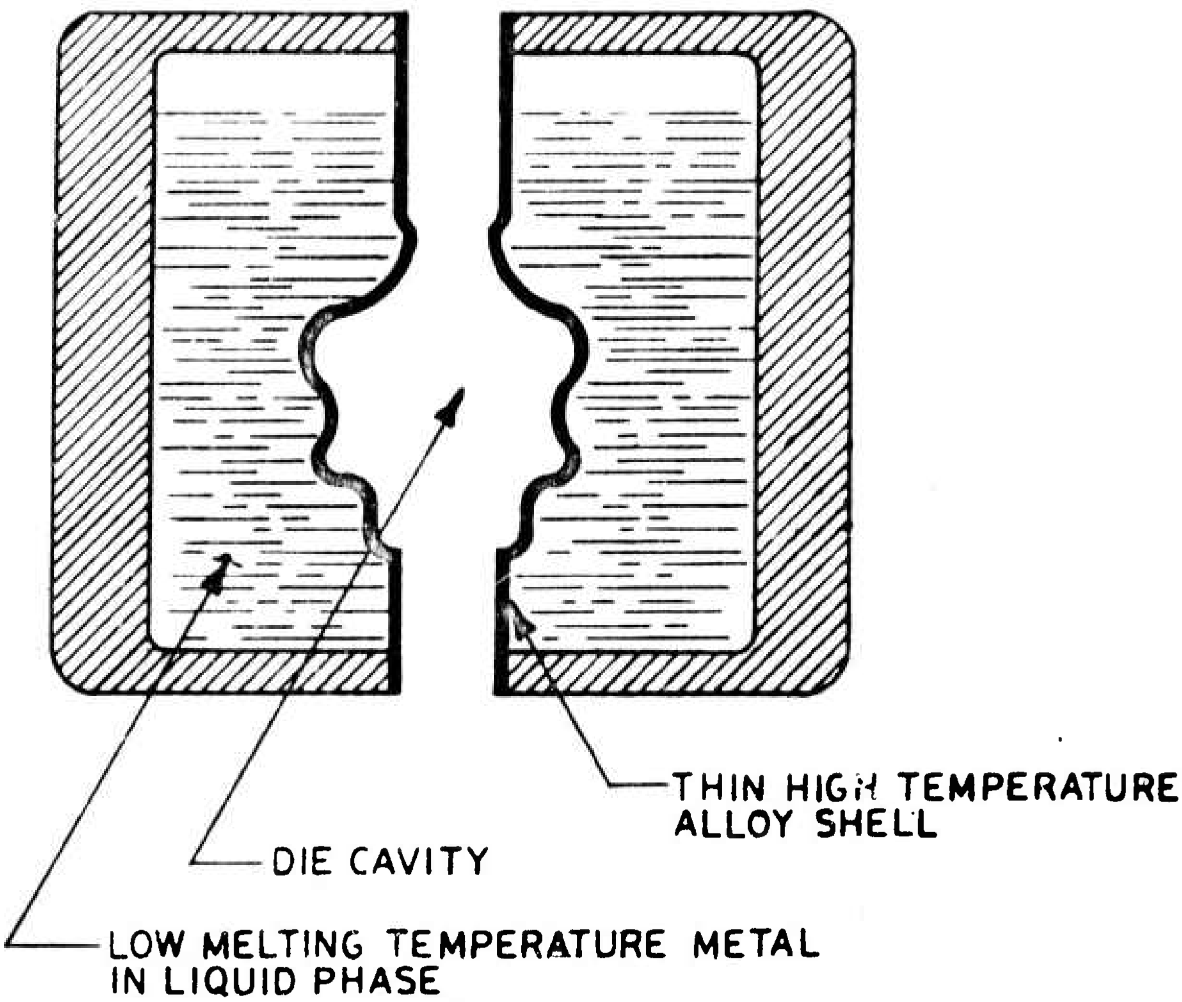


Figure 7. Schematic of Composite Die.

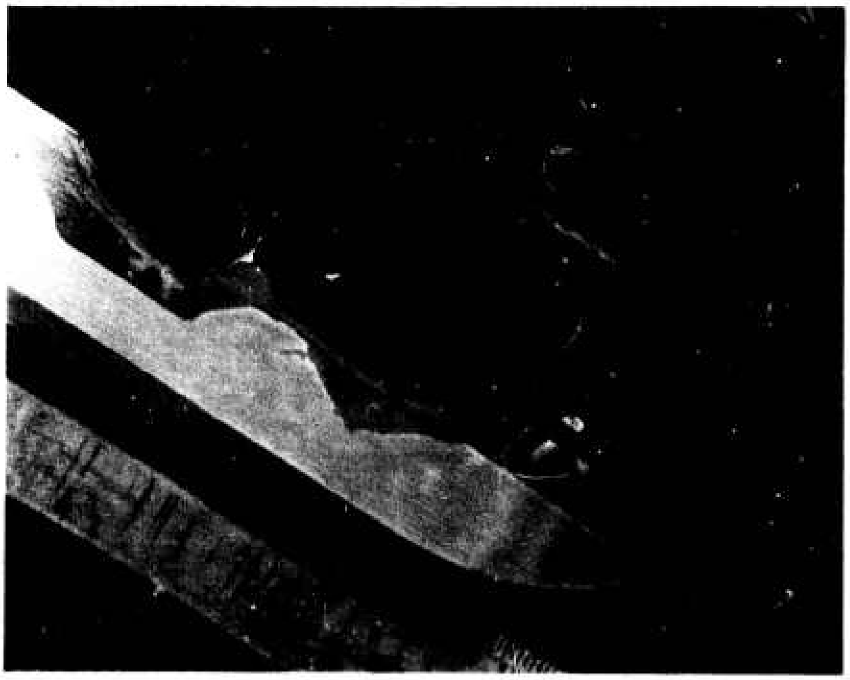


Figure 8. Cross section photograph of composite Hipocast die after failure at 90 cycles.

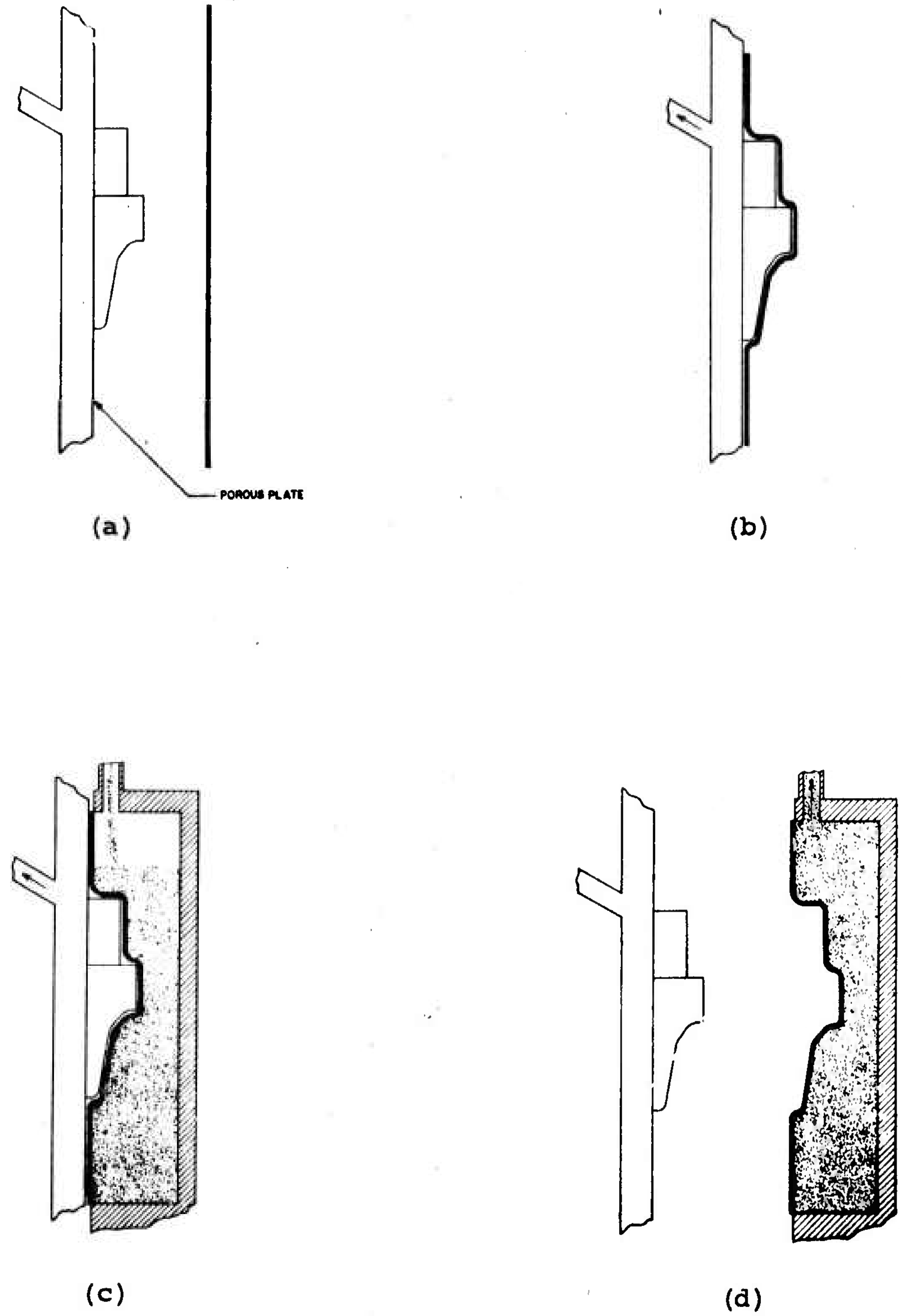


Figure 9. Sequence of mold preparation for Hipo-V Process.

Figure 10. Photographs of first Hipo-V casting.

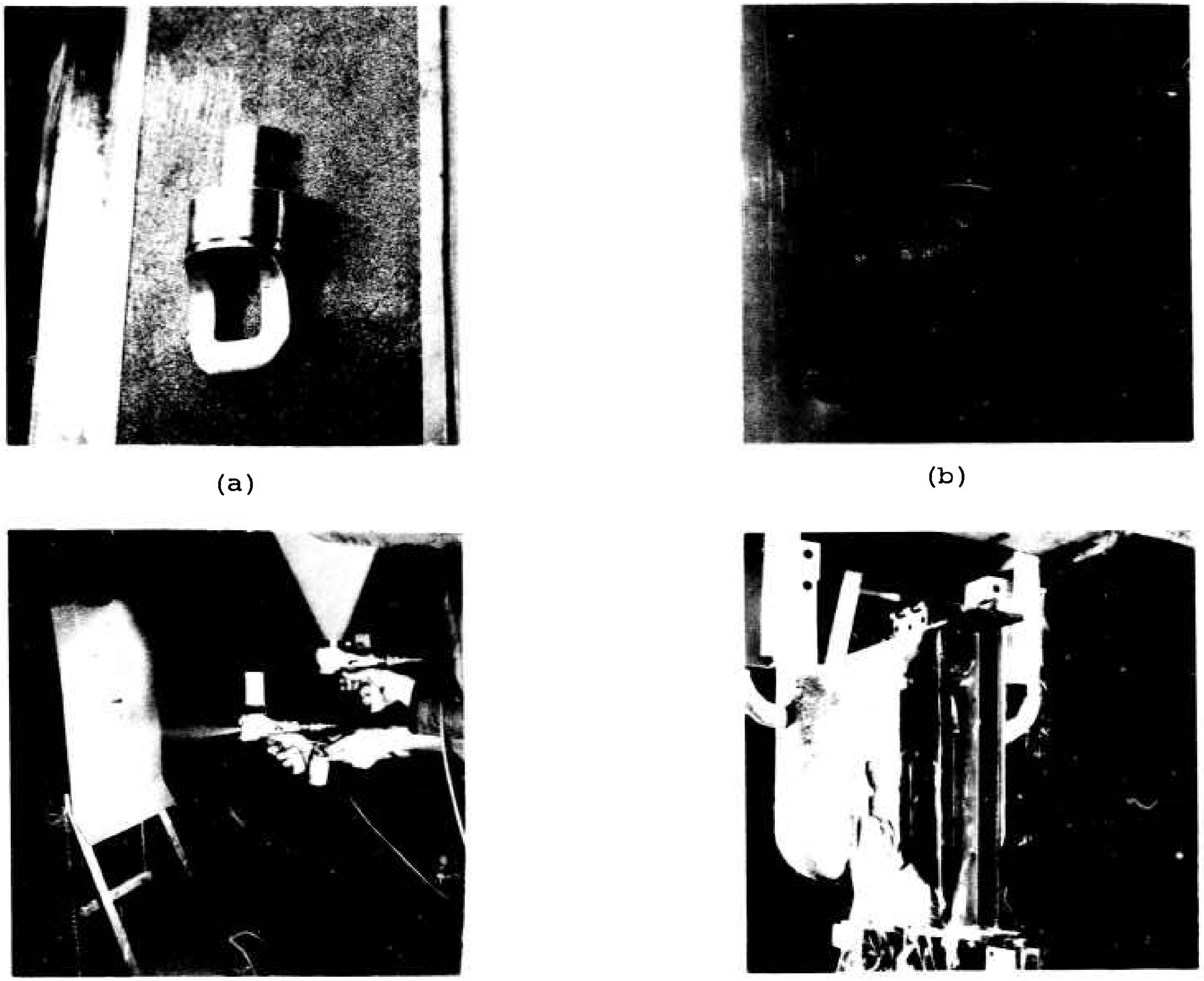
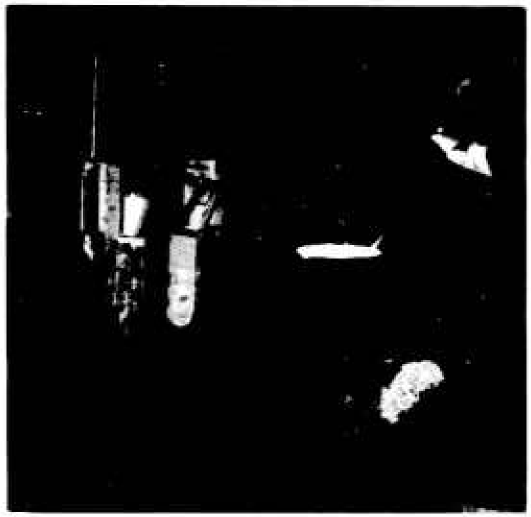
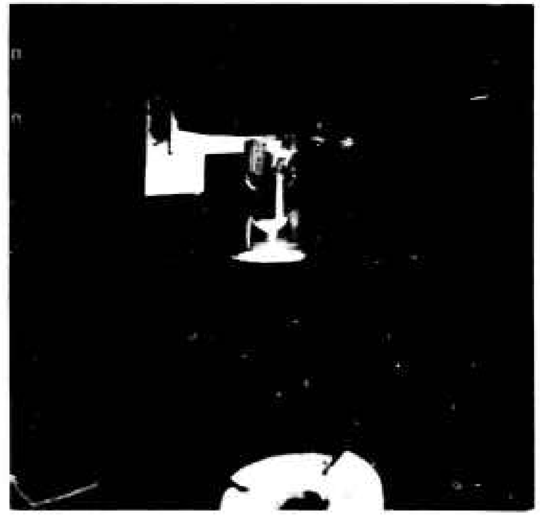

(a) (b) (c) (d)

Figure 11. Operation sequence for augmented Hipo-V Process.

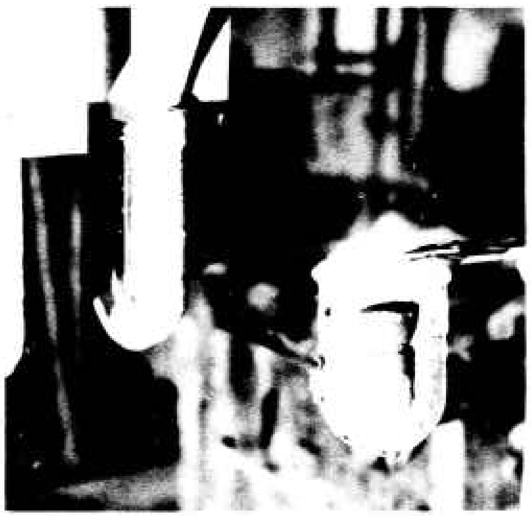
cont.



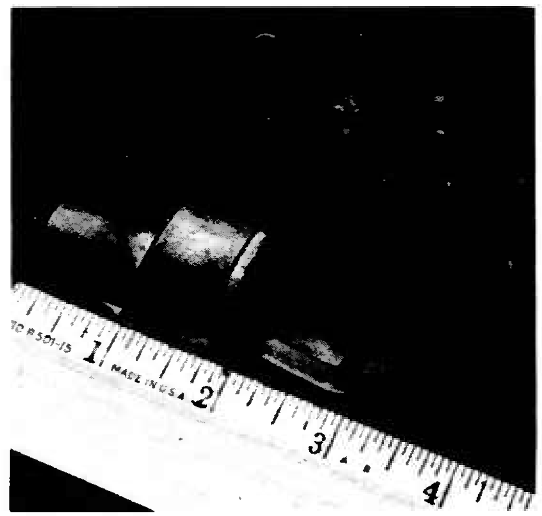
(e)



(f)



(g)



(h)

Continuation of Figure 11.

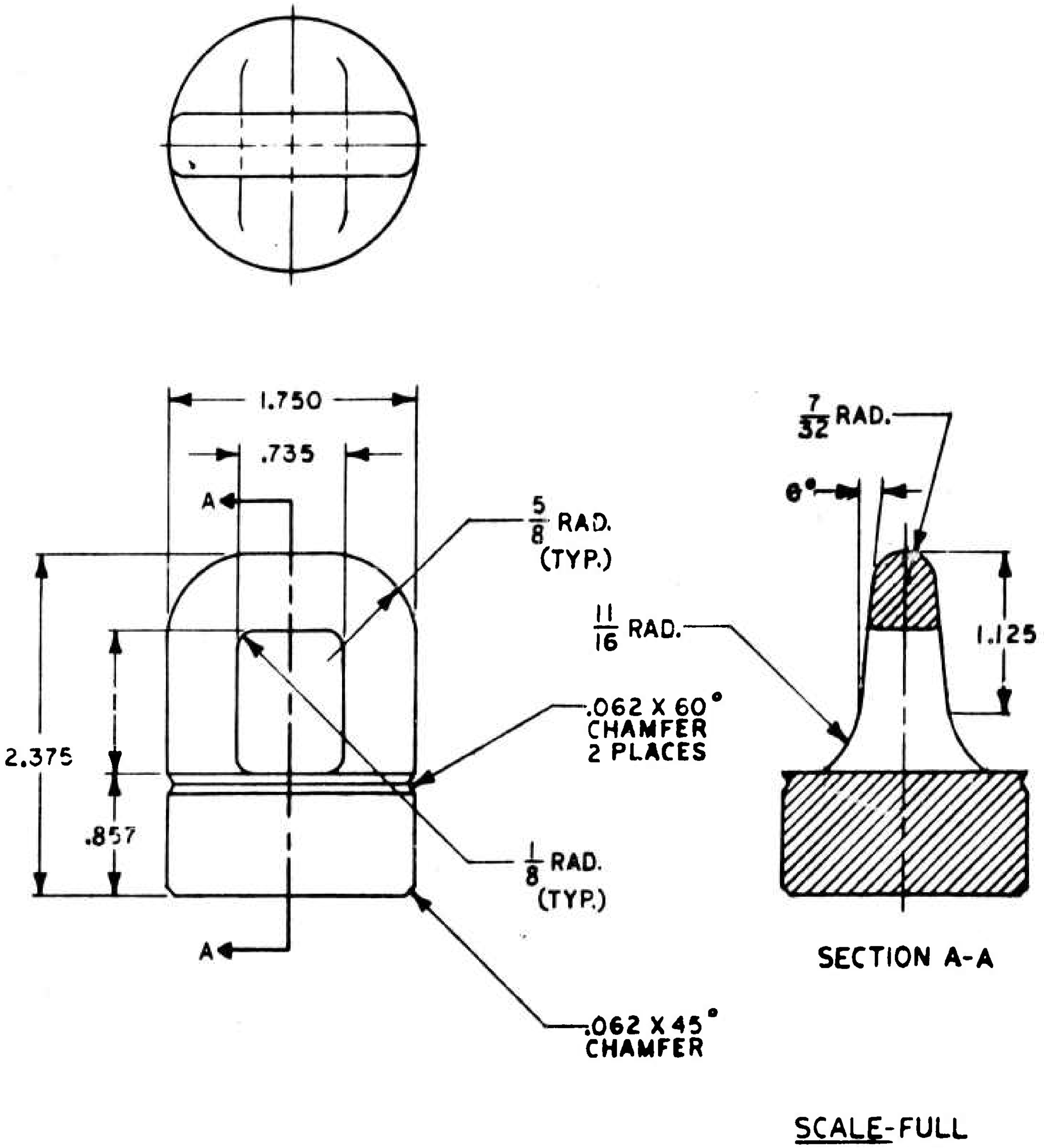


Figure 12. Drawing of suspension Bomb Lug.

Figure 13. Apparatus used to CLA pour Rheocast aluminum.

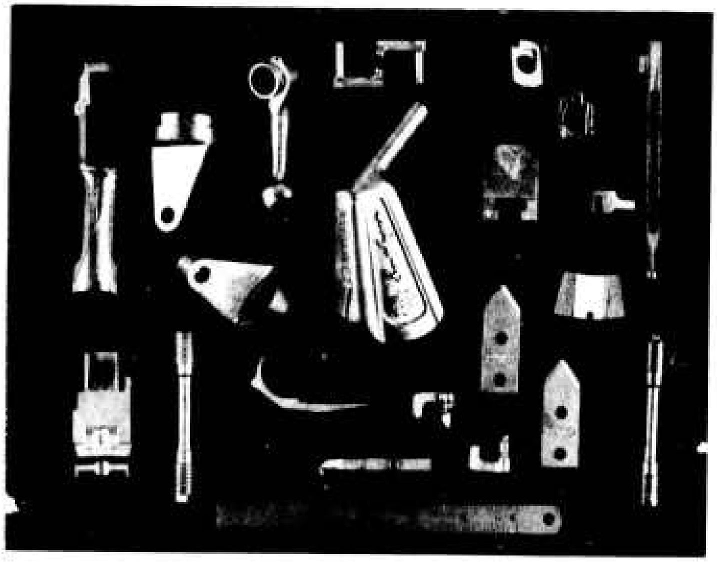


Figure 14. Collection of parts cast by CLA process in semi-solid 35S aluminum.

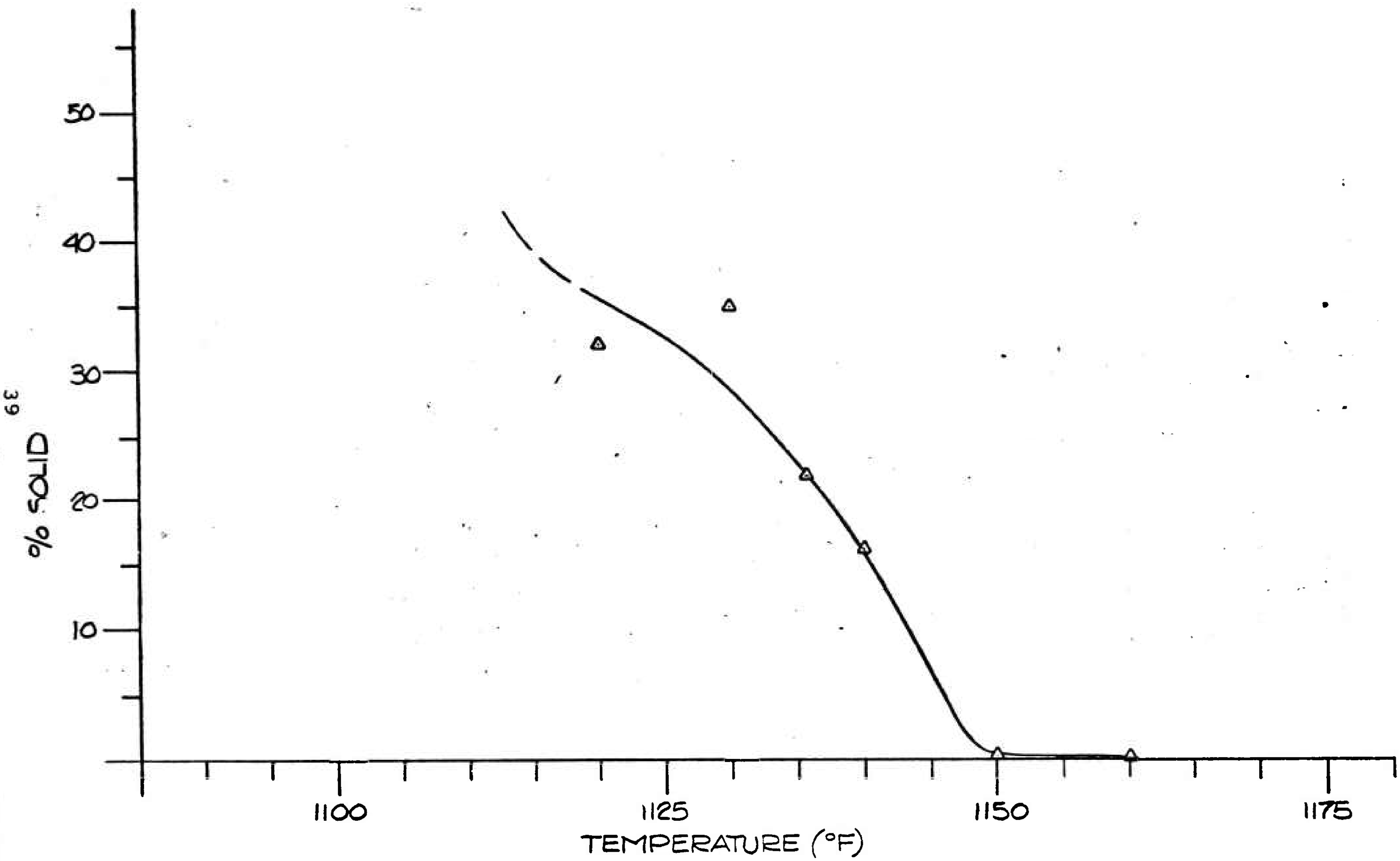


Figure 15. Solid composition versus temperature for 355 aluminum.

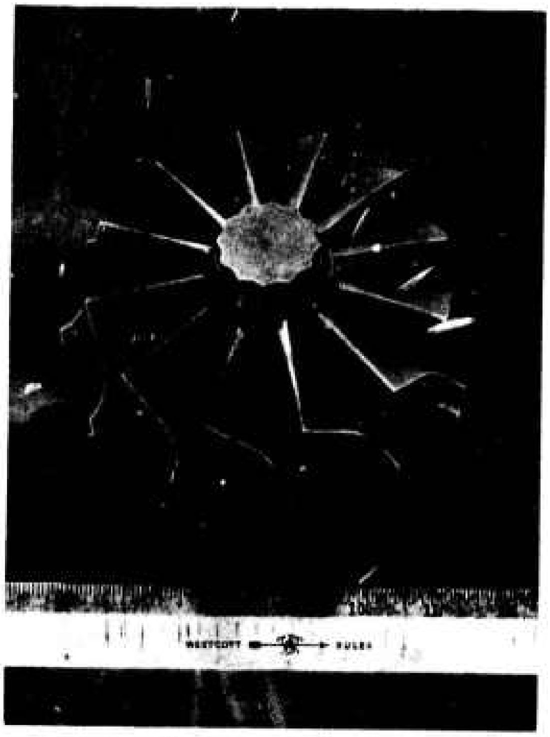


Figure 16. Large Switzer Turbine Wheel.

Figure 17. Small Switzer Wheel.

Figure 18. Comparison of internal grain structure characteristic of vacuum (top) and CLA (bottom) cast Switzer wheels in Inco 713LC.

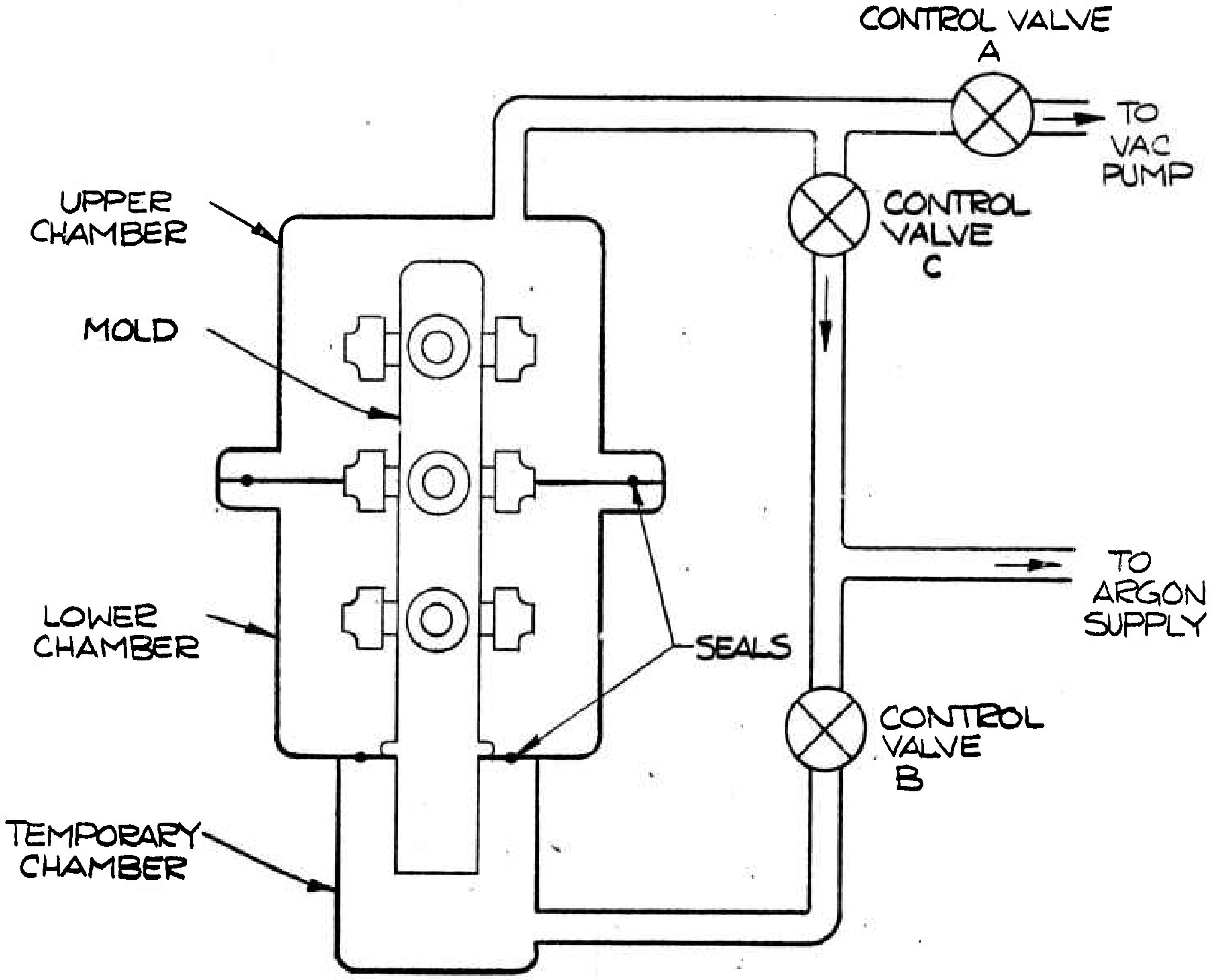


FIGURE 19
SCHEMATIC REPRESENTATION OF ARGON
SHIELDING SYSTEM

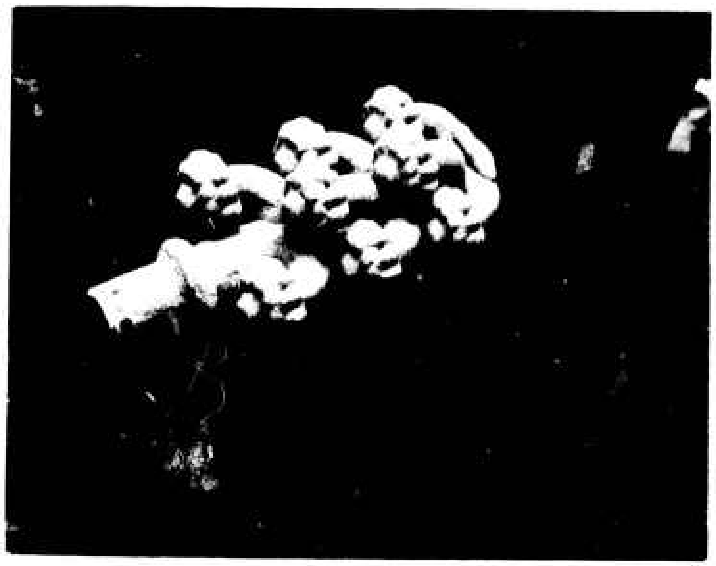


Figure 20. Sprue design for CLA casting turbine wheels.

TABLE I.

Nominal Composition

Alloy	C	Mn	Si	Cr	Mo	Al	Fe	Zr	Cb	Ti	B
Inco 713LC	.05	-	-	12	4.5	5.9	-	.1	2	.6	.01
GMR 235	.15	.3	.45	15.5	5.25	3.75	10	-	-	2	.05

- -

TABLE II.

MECHANICAL PROPERTIES
(Data indicated is average of at least two points)

Test	Specification	CLA Results	Vac. Results
GMR 235			
1) Stress Rupture 1500F-35 ksi	75 hr.	82.3 hr.	84.5 hr.
Stress increased 5 ksi/hr. after 75 hr.	5% elong.	16.2%	13.9%
2) Stress Rupture 1500F-50 ksi	23 hr.	26.5 hr.	27.3 hr.
Stress increase 5 ksi/hr. after 23 hr.	5% elong.	15.5%	18.3%
3) Tensile 1200F	85 ksi UTS	119 ksi	
	80 ksi yield	104 ksi	
	2% elong.	3%	
713LC			
1) Stress Rupture 1800F-22 ksi	30 hr.	38.7 hr.	34.7 hr.
	5% elong.	3.7%	7%
2) Tensile Room temp.	110 ksi UTS	135 ksi	126 ksi
	100 ksi yield	126 ksi	116 ksi
	3%	4.5%	3½%

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(10) U.S. Patent 3,646,990, Raymond E. Cross, "Die Casting Machine".

(11) R. C. Cornell, "Metal Flow in Die Casting", Army Materials Technology Conference on Solidification Technology, 22-25 October, 1972.

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Contract Code: DAAG46-73-C-0112
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